

ALICE



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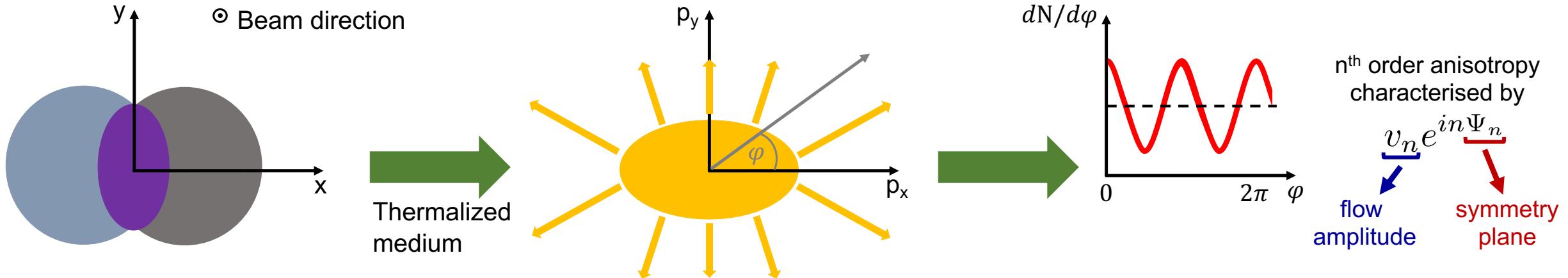
New advancements in symmetry plane correlations and multiharmonic fluctuations in heavy-ion collisions with ALICE

Marcel Lesch
on behalf of the ALICE Collaboration

Technical University of Munich

ICHEP 2022, Bologna, Italy
08th of July 2022

QGP studies with anisotropic flow



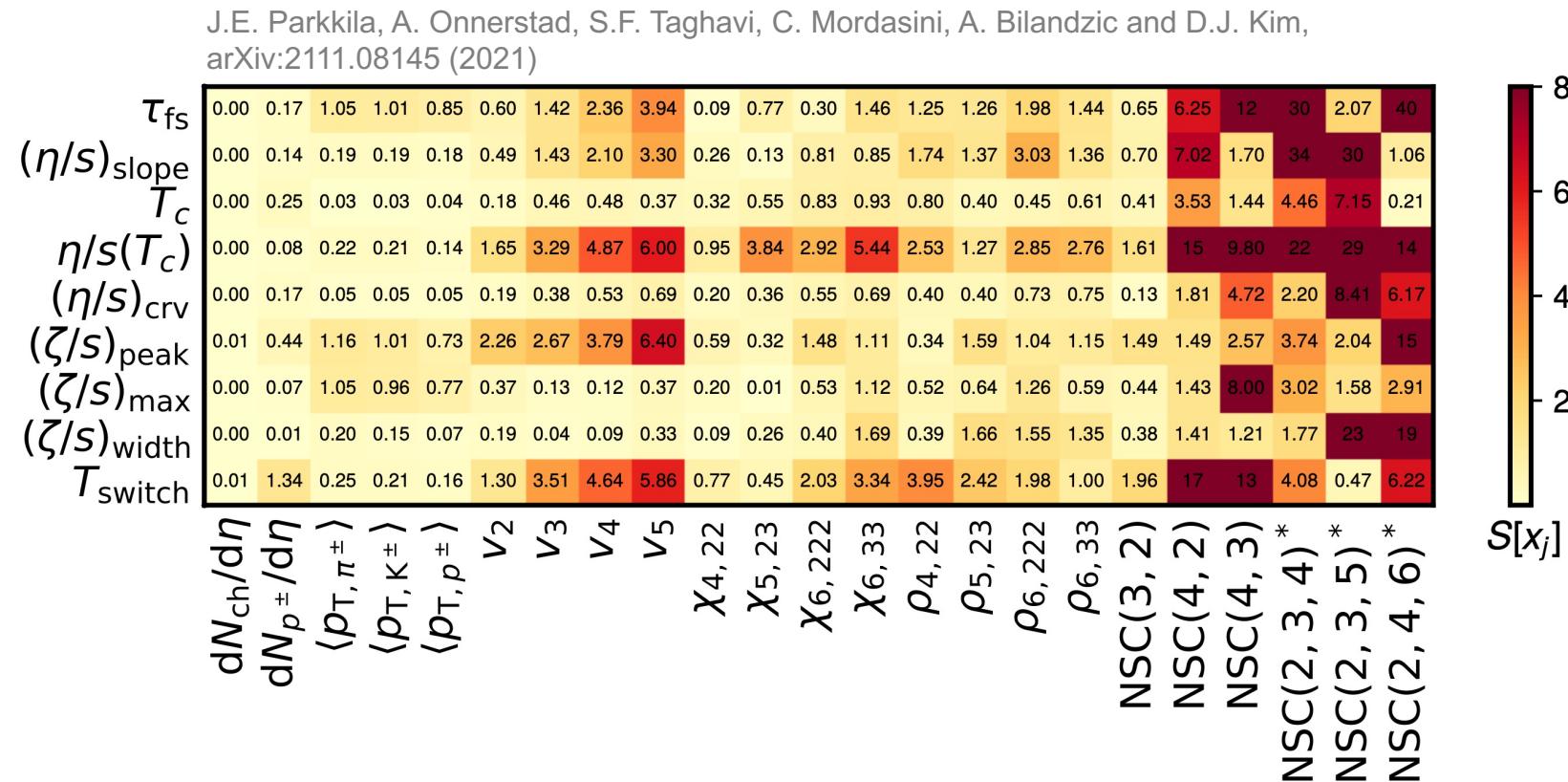
- **Anisotropic Flow:** Transition from **anisotropy in coordinate space** to **anisotropy in momentum space** via thermalized medium
- Final state anisotropies v_n and Ψ_n contain information on initial state and QGP
- Modelling of heavy-ion collisions involves initial state + hydrodynamics + hadronic afterburner
- Bayesian analyses: Most successful tool to extract QGP parameters from experimental data with model



QGP studies with anisotropic flow

- Higher sensitivity of correlations between ν_n and/or Ψ_n to QGP parameters in Bayesian analyses
→ Precision measurements of observables reflecting non-linear hydrodynamic responses needed
- In this presentation:
 - Asymmetric cumulants (AC) for different moments of flow amplitudes
 - Symmetry plane correlations (SPC)
 - Comparisons to state-of-the-art model tuning of T_RENTo + iEBE-VISHNU for SPC and AC

J. E. Bernhard, J. S. Moreland, and S. A. Bass,
Nature Phys. 15 no. 11, (2019) 1113–1117





Asymmetric Cumulants of v_m and v_n

- AC: Cumulants involving higher moments of v_m and v_n
- General expression of $\text{AC}_{a,1}$

$$\text{AC}_{a,1}(2,3) \equiv \langle v_2^{2a} v_3^2 \rangle_c$$

$$\text{AC}_{a,1}(3,2) \equiv \langle v_3^{2a} v_2^2 \rangle_c$$

A. Bilandzic, ML, C. Mordasini and S.F. Taghavi,
PRC 105, 024912 (2022)

- For $a=1$: $\text{AC}_{a,1} \rightarrow$ Symmetric Cumulant (SC)
- $\text{AC}_{a,1}$ depend on the magnitudes of the flow harmonics



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- $\text{AC}_{a,1}$ depend on the magnitudes of the flow harmonics

Normalisation

- NAC: Normalised asymmetric cumulants for higher moments of v_m and v_n

$$\text{NAC}_{a,1}(2,3) = \frac{\langle v_2^{2a} v_3^2 \rangle_c}{\langle v_2^2 \rangle^a \langle v_3^2 \rangle}$$

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A. Bilandzic, ML, C. Mordasini and S.F. Taghavi,
PRC 105, 024912 (2022)

- Magnitude dependence of AC on flow harmonics removed by normalisation
- For $a=1$: $\text{NAC}_{a,1} \rightarrow$ Normalised Symmetric Cumulant (NSC)



Normalised Asymmetric Cumulants of v_m and v_n

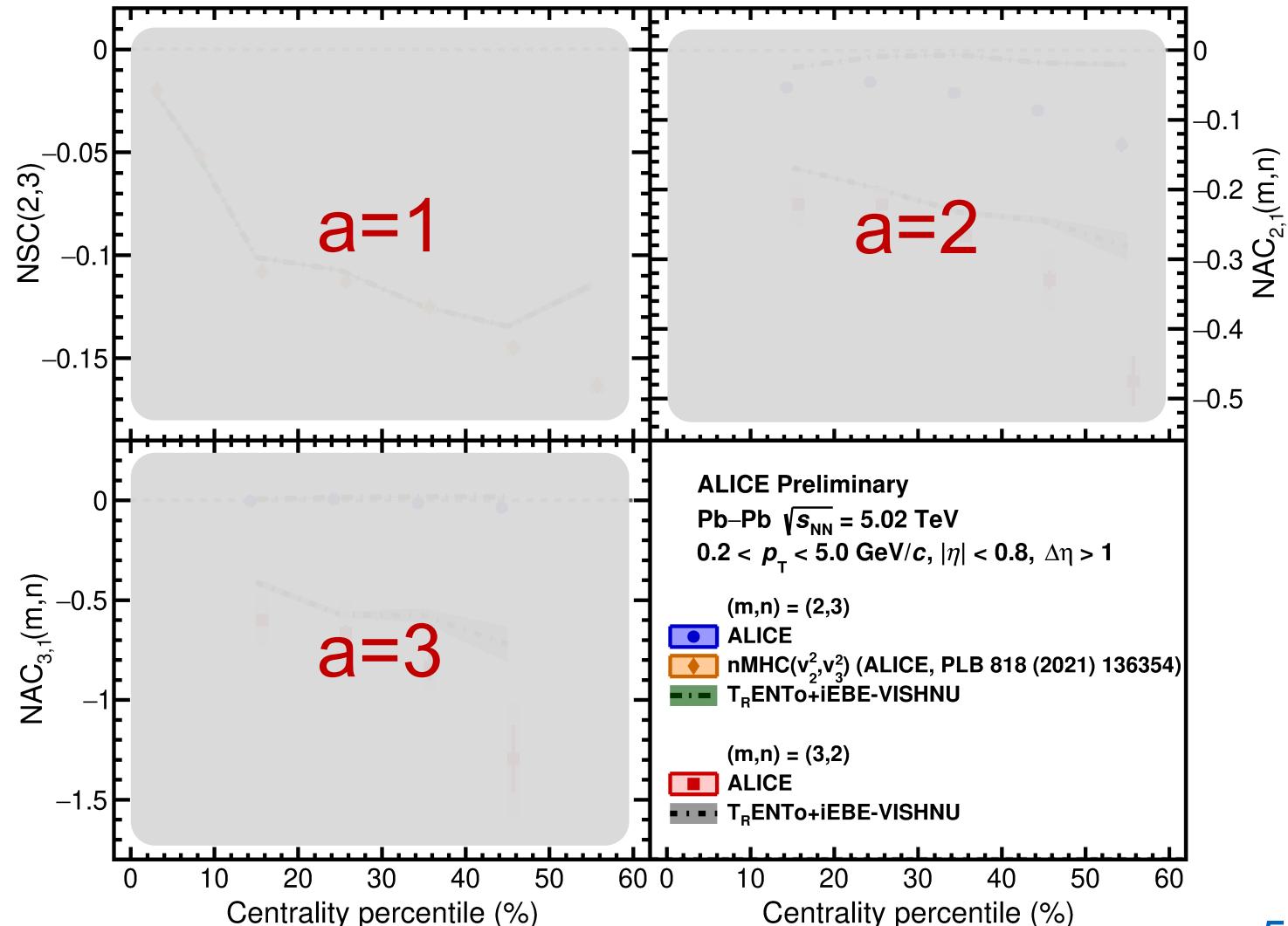
- Measurement of NAC in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$ with ALICE

New

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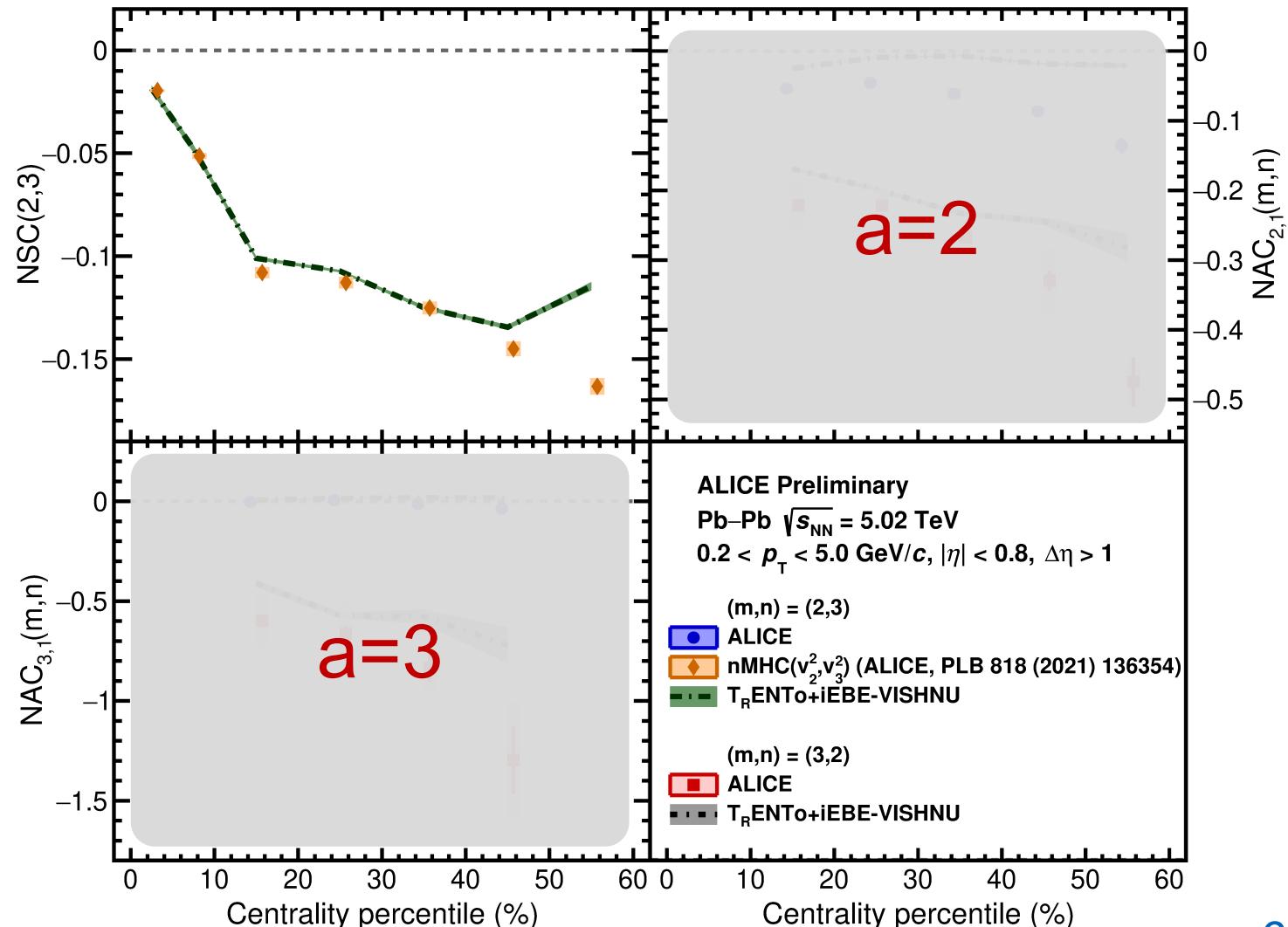
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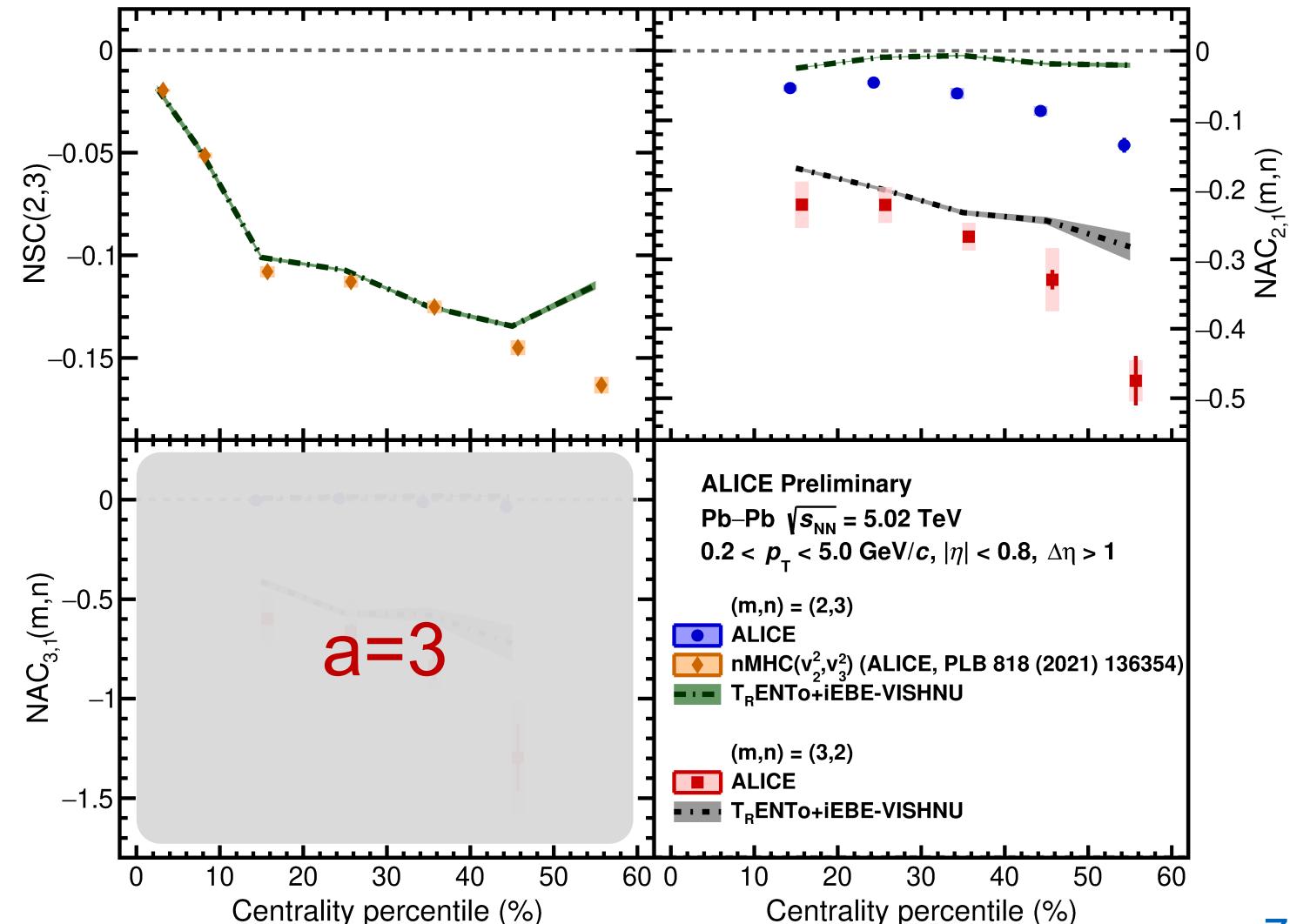
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- Increasing value of index a

- $\text{NAC}_{a,1}(2,3)$: Decreasing anticorrelation
- $\text{NAC}_{a,1}(3,2)$: Increasing anticorrelation





Normalised Asymmetric Cumulants of v_m and v_n

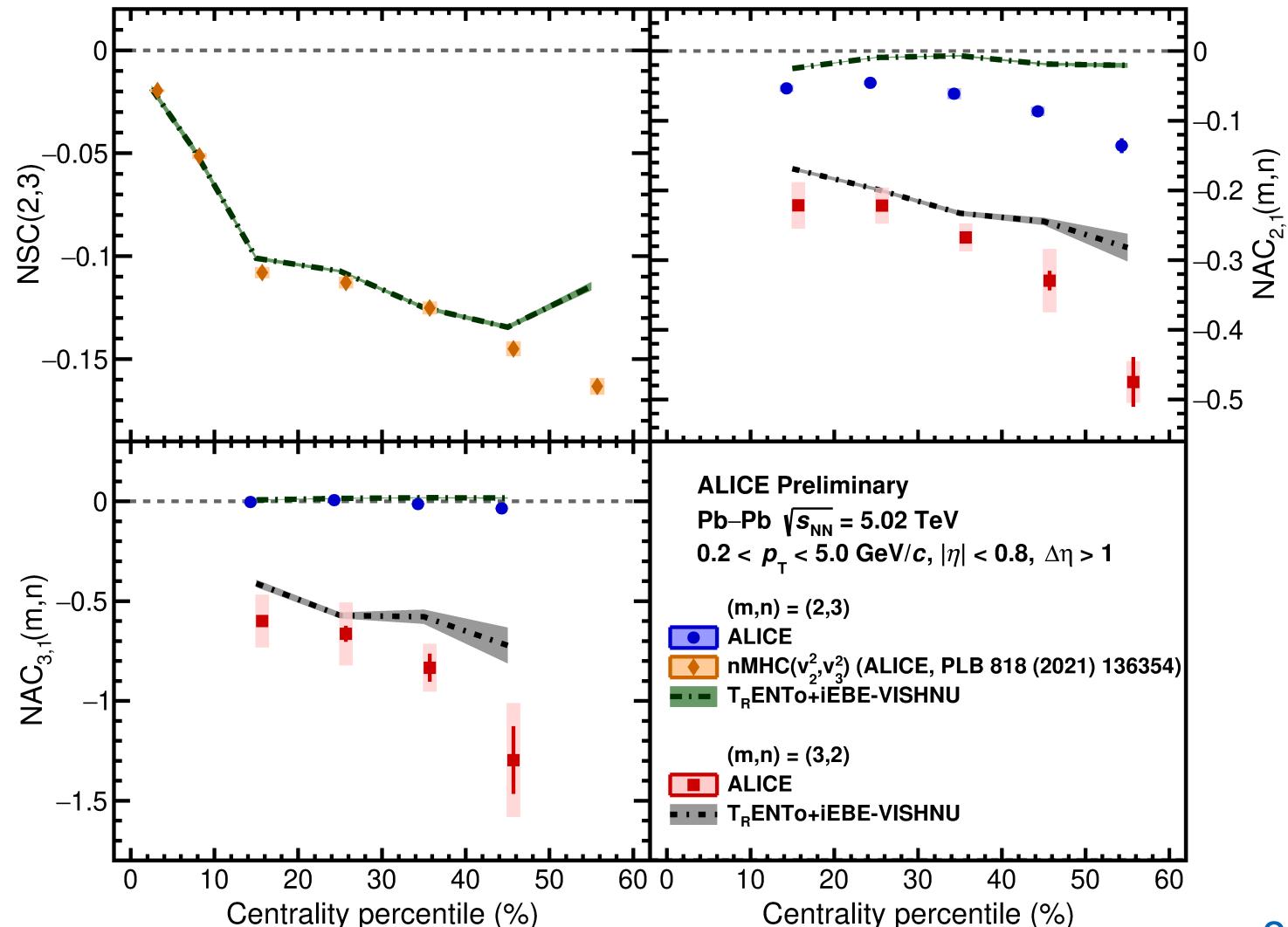
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New





Symmetry Plane Correlations (SPC)

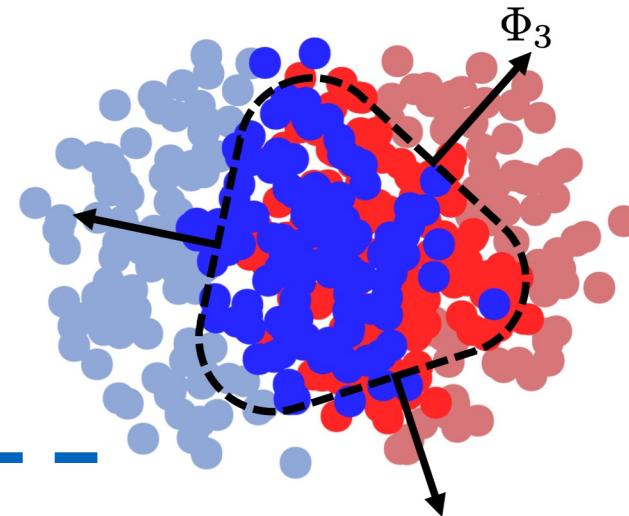
- Comparison of SPC in the initial and final state is sensitive to **linear** and **non-linear** response, e.g.

linear

$$\langle \cos[4(\Psi_4 - \Psi_2)] \rangle = \langle \cos[4(\Phi_4 - \Phi_2)] \rangle$$

non-linear

$$\langle \cos[4(\Psi_4 - \Psi_2)] \rangle \neq \langle \cos[4(\Phi_4 - \Phi_2)] \rangle$$





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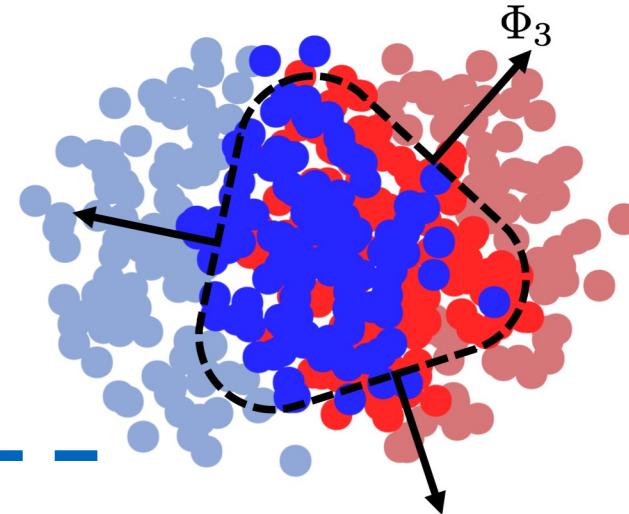
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- Previous work: **Scalar Product (SP) Method**

STAR Collaboration. PRC 66, 034904, 2002

R. S. Bhalerao, J.-Y. Ollitrault and S. Pal., PRC 88, 024909, 2013

- Example:

$$\langle \cos[4(\Psi_4 - \Psi_2)] \rangle_{\text{SP}} = \frac{\langle v_2^2 v_4 \cos[4(\Psi_4 - \Psi_2)] \rangle}{\sqrt{\langle v_2^4 \rangle \langle v_4^2 \rangle}}$$

→ Correlations between flow amplitudes v_n
neglected



Symmetry Plane Correlations (SPC)

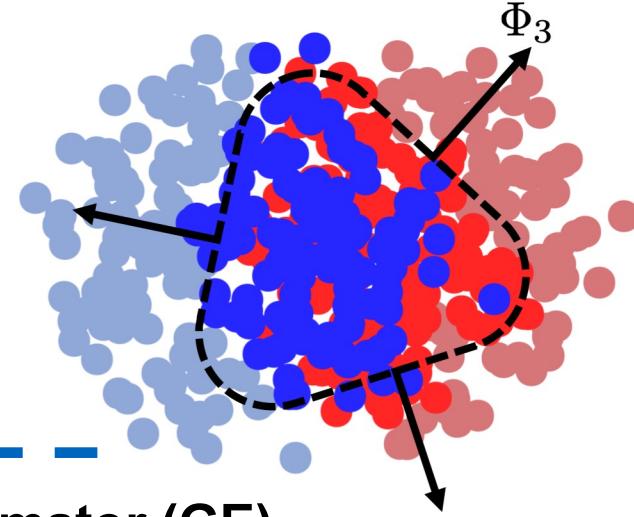
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→ Correlations between flow amplitudes v_n neglected

- New: **Gaussian Estimator (GE)**

A. Bilandzic, ML and S. F. Taghavi, PRC 102, 024910 – 2020

- Example:

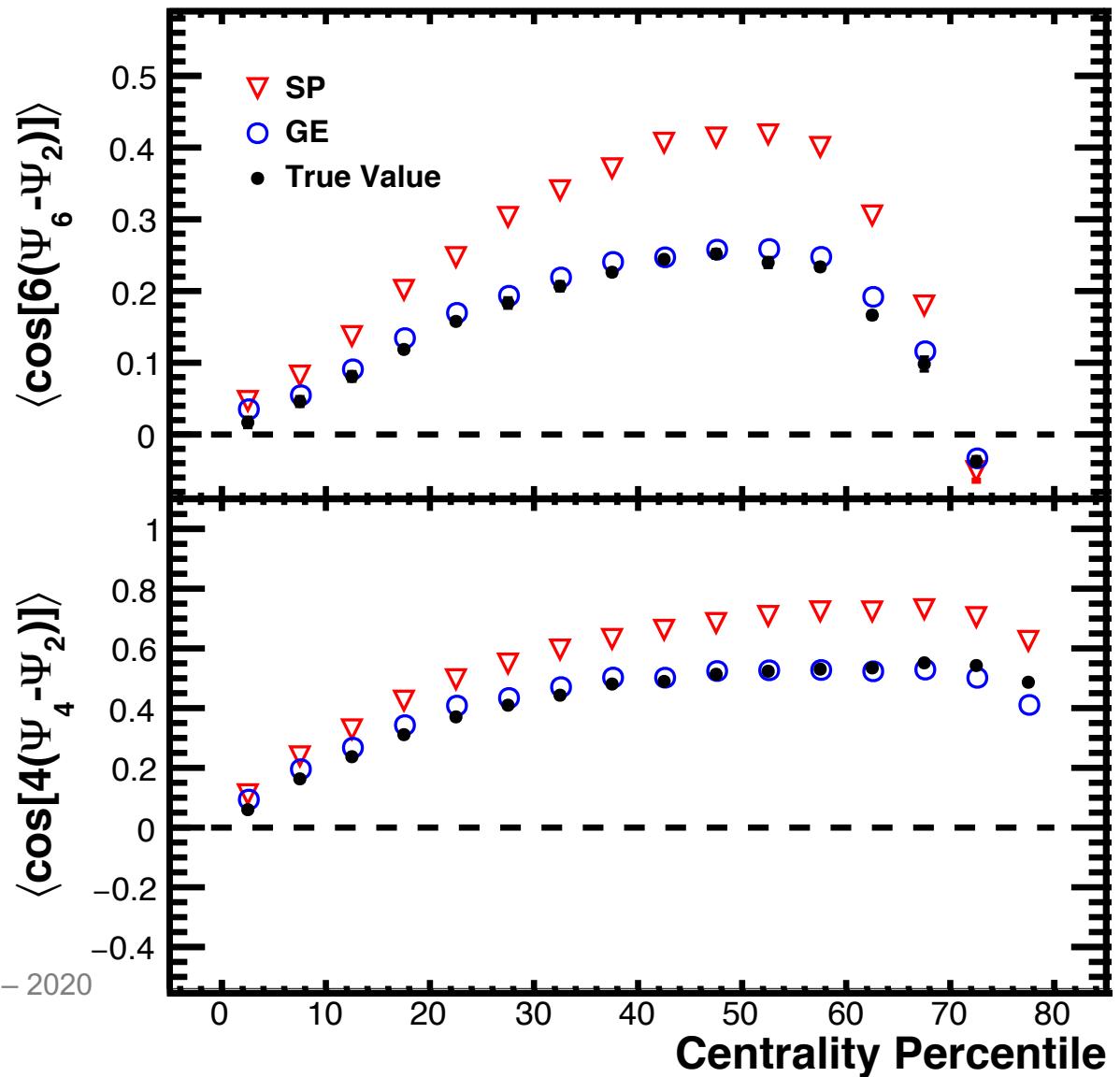
$$\langle \cos[4(\Psi_4 - \Psi_2)] \rangle_{\text{GE}} = \sqrt{\frac{\pi}{4}} \frac{\langle v_2^2 v_4 \cos[4(\Psi_4 - \Psi_2)] \rangle}{\sqrt{\langle v_2^4 v_4^2 \rangle}}$$

- Not sensitive to correlations between flow amplitudes
- Overcomes main bias of previous estimators

Gaussian Estimator - a new experimental technique for SPC



- Comparison of GE to SP and “true” value in iEBE-VISHNU (Pb–Pb at $\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}$)
- Clear improvement over existing SP method
- GE closer to the “true” value of SPC in central to semicentral collisions
- GE not sensitive to the correlations between different flow amplitudes!

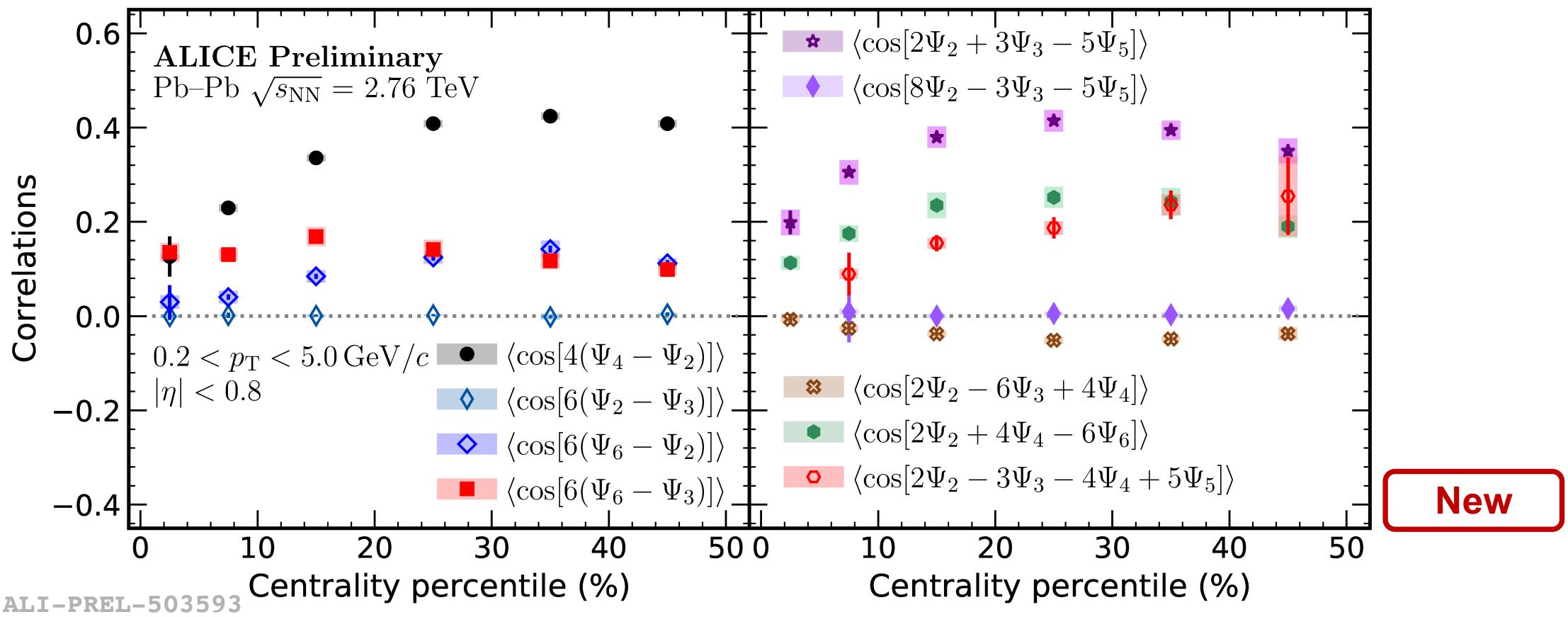


A. Bilandzic, ML and S. F. Taghavi, PRC 102, 024910 – 2020



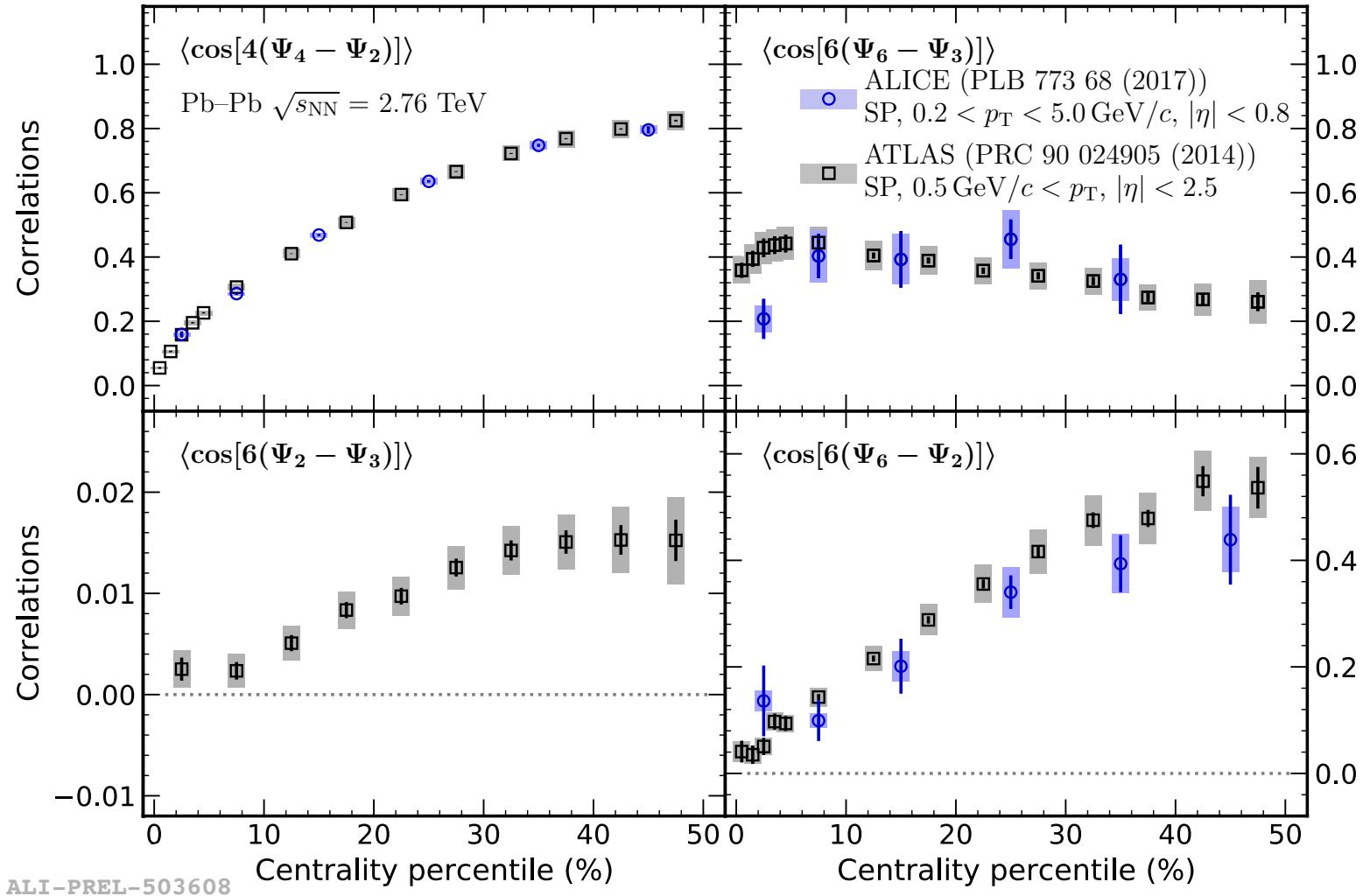
New measurements of SPC in ALICE

- Measurement of SPC between two and three symmetry planes with various magnitudes and centrality dependencies in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}$
- First experimental measurement of correlation between four symmetry planes $\Psi_2, \Psi_3, \Psi_4, \Psi_5$





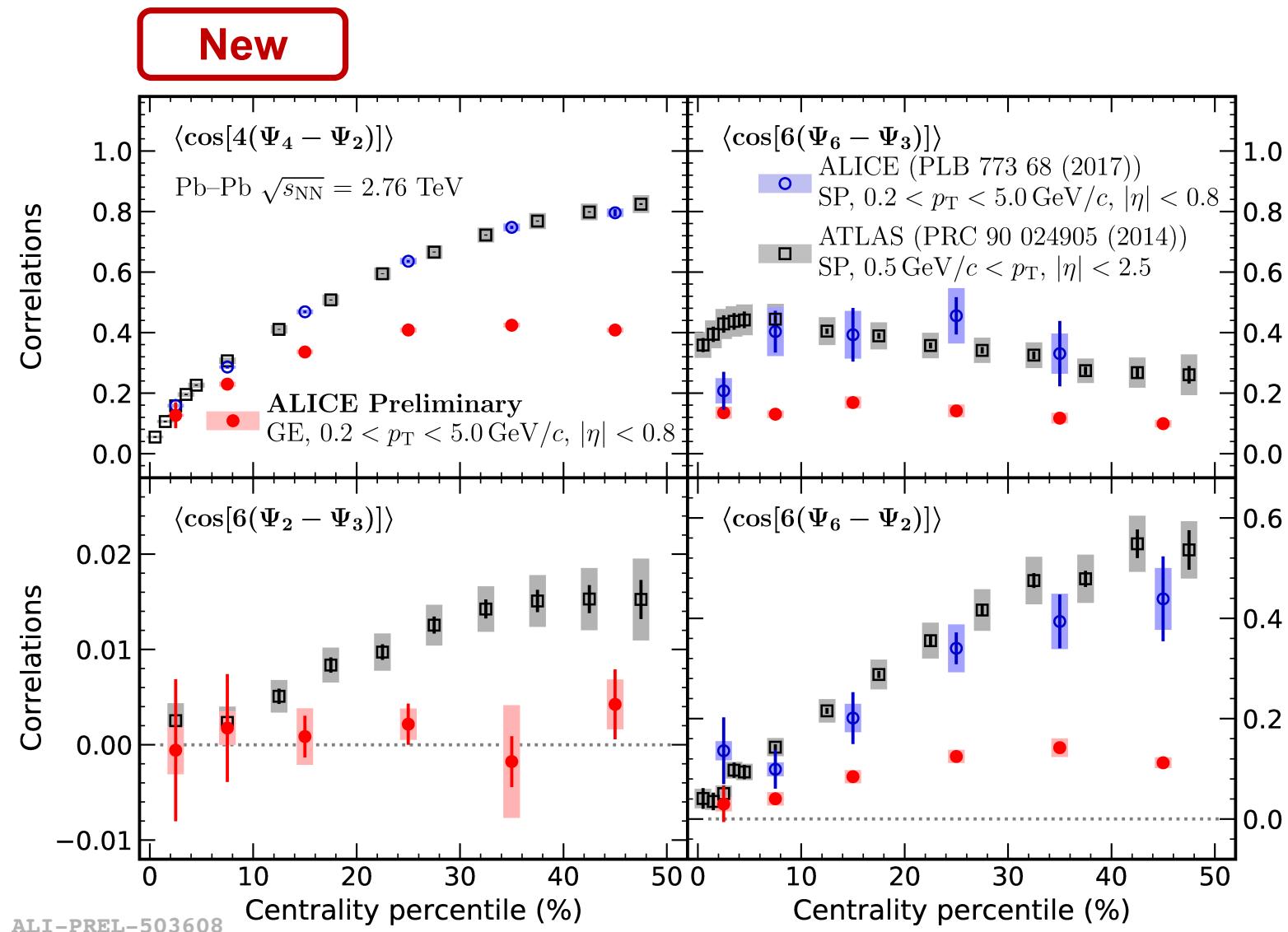
Comparison between GE and SP





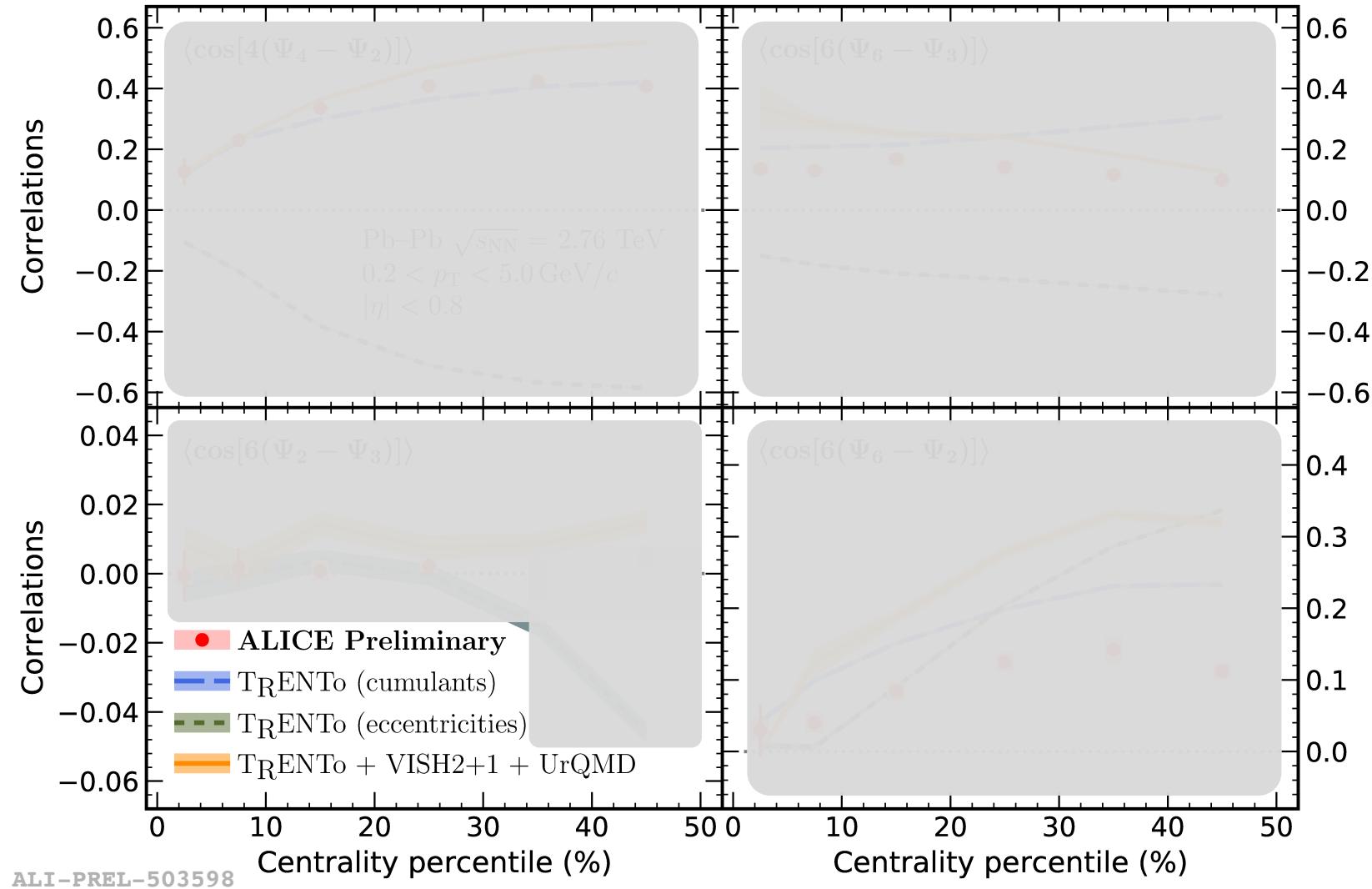
Comparison between GE and SP

- Results of SPC via GE significantly smaller than SP method
- Correlation between Ψ_2 and Ψ_3 small but non-zero in SP
→ correlated symmetry planes
- Result of GE compatible with zero in all centrality bins for Ψ_2 and Ψ_3
→ possibly uncorrelated symmetry planes





Correlations between two symmetry planes

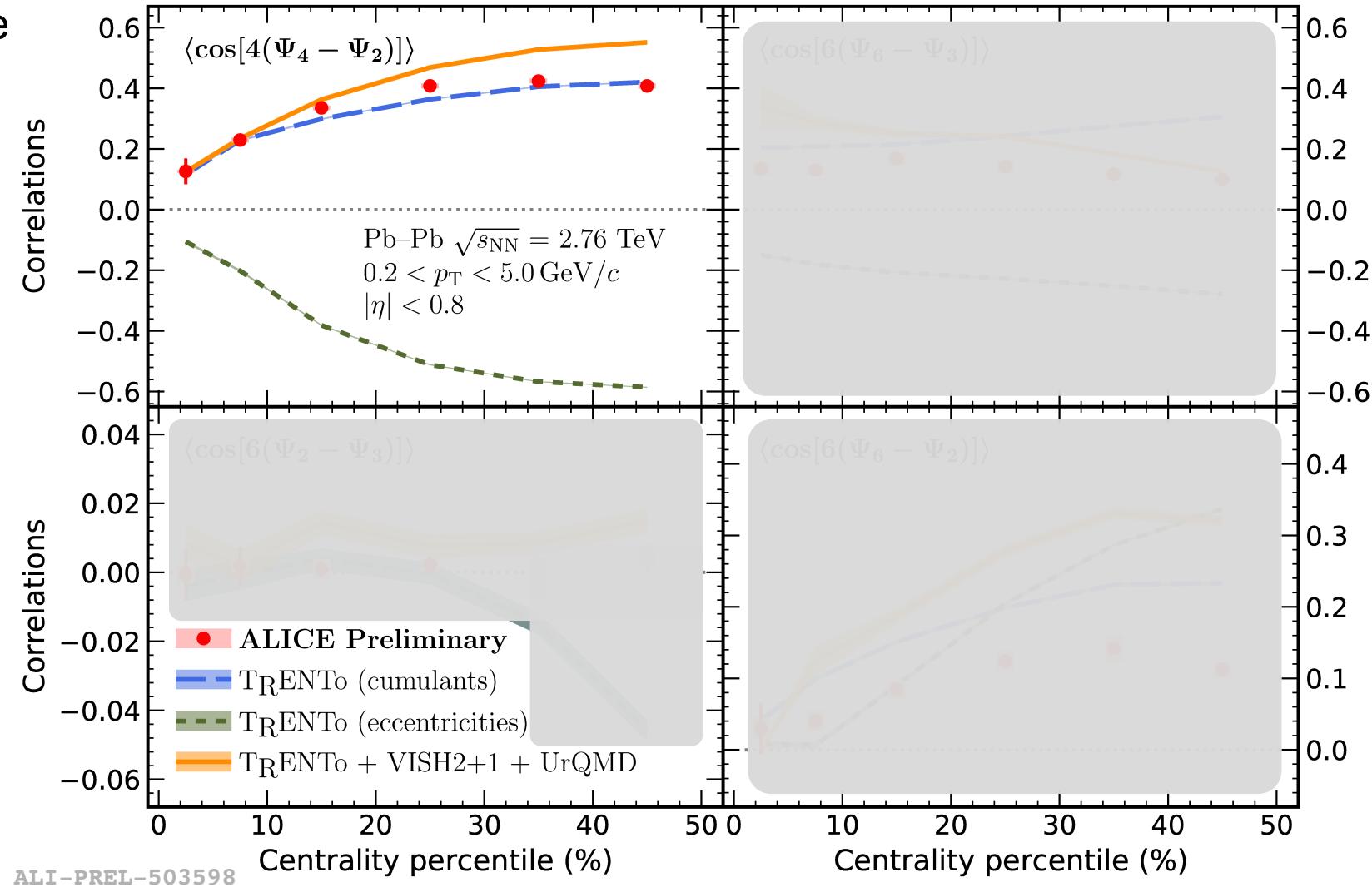


New



Correlations between two symmetry planes

- Ψ_2 and Ψ_4 correlated in final state
 - Data only well reproduced in the linear-response regime

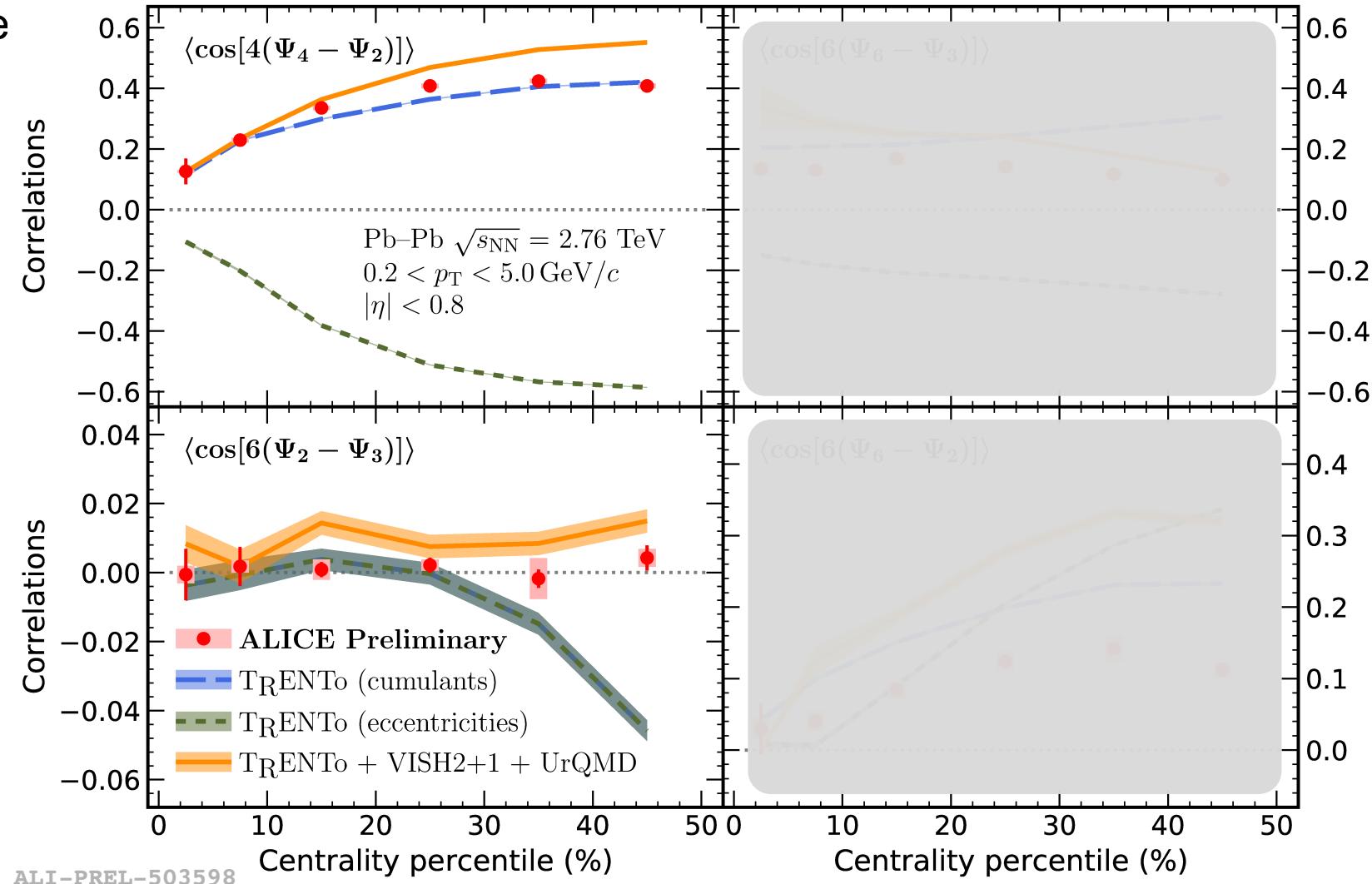


New



Correlations between two symmetry planes

- Ψ_2 and Ψ_4 correlated in final state
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- SPC of Ψ_2 and Ψ_3 zero within uncertainties
 - Correlation extremely small or completely absent
 - Correlations in initial state lost/suppressed during hydrodynamic evolution

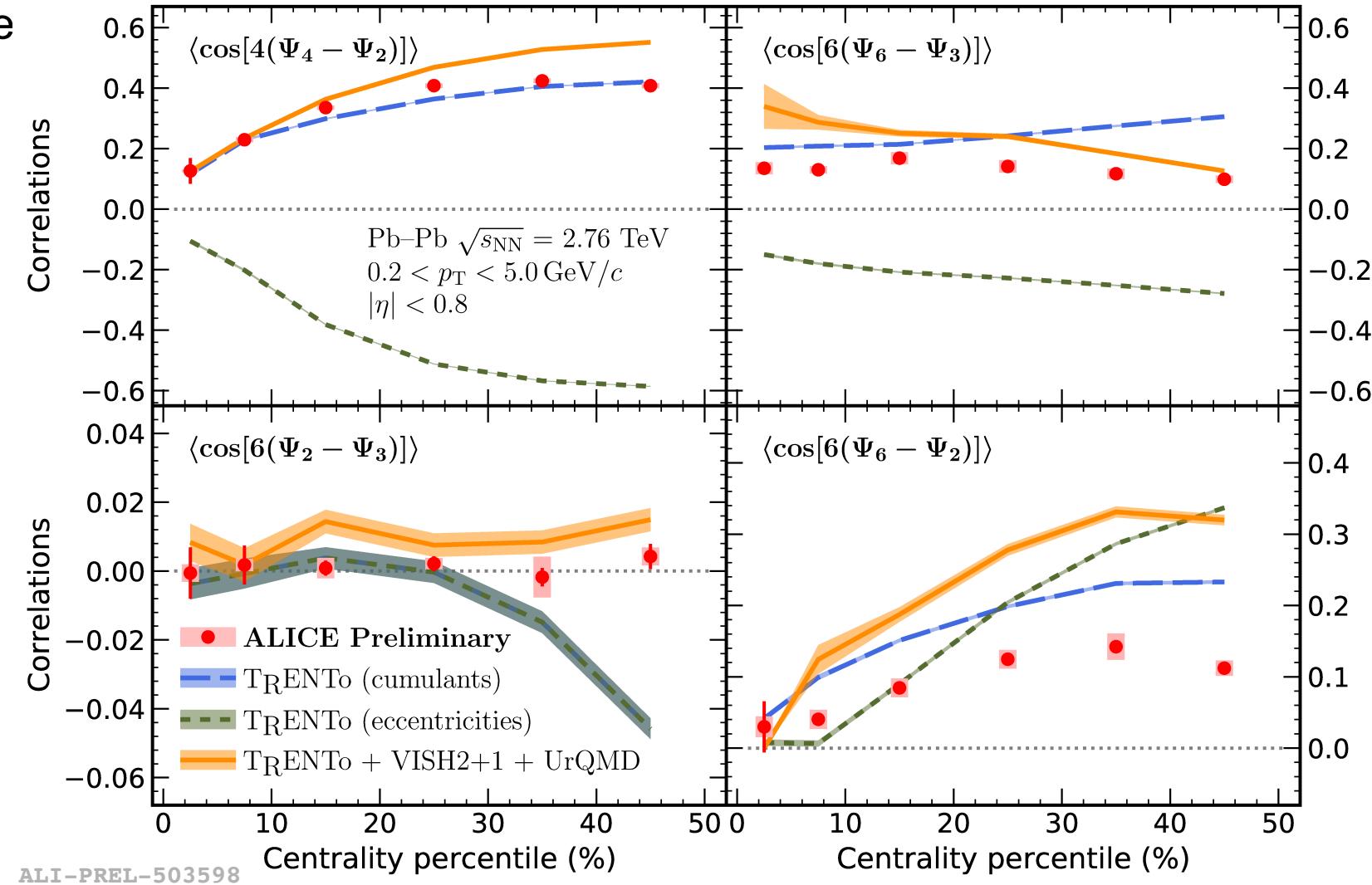


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- Large deviation of the model from data for SPC involving Ψ_6

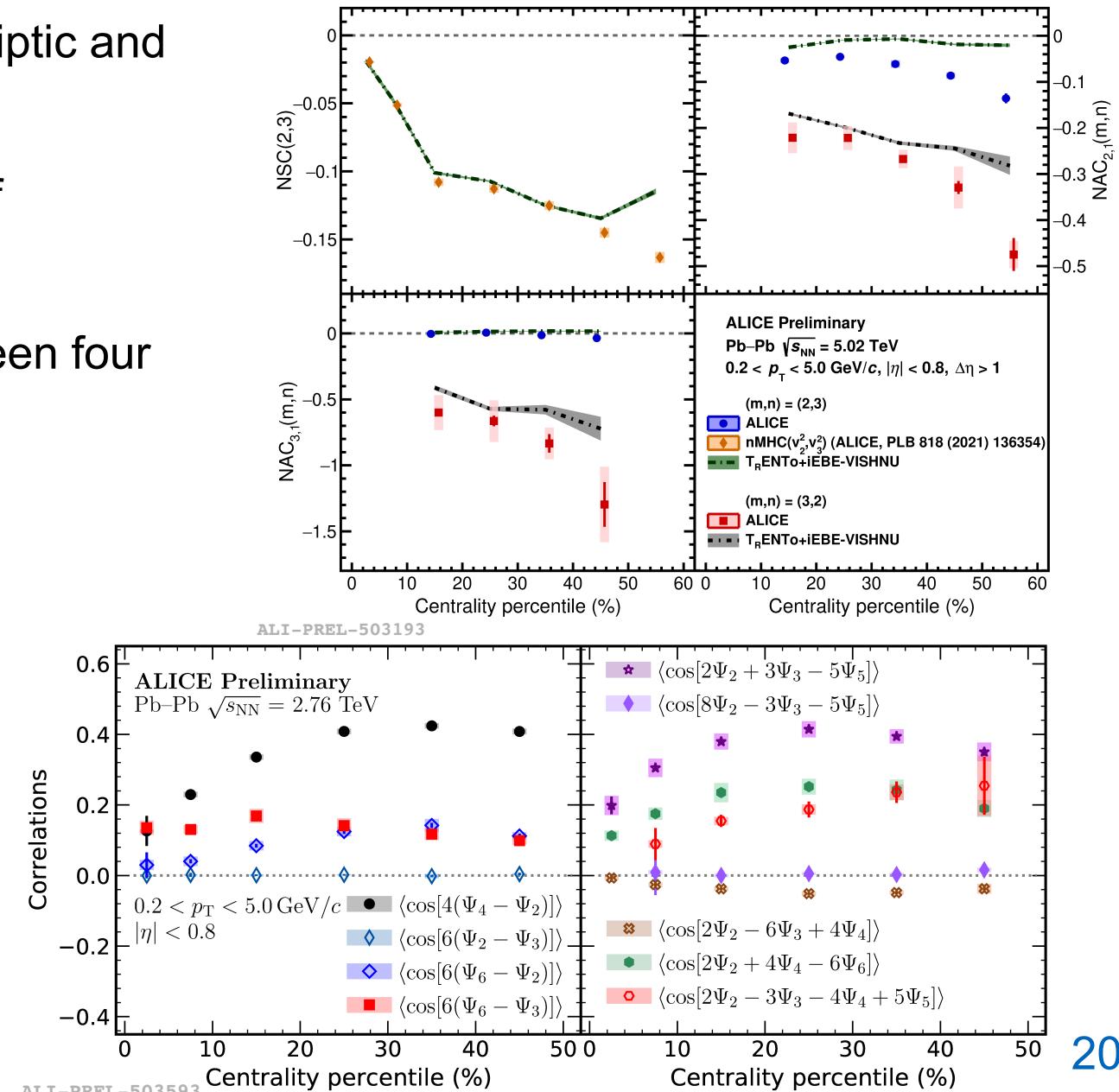


New



Summary and Outlook

- First measurements of (AC &) NAC between elliptic and triangular flow
- First measurements of SPC without influence of correlations between flow amplitudes
- First experimental measurements of SPC between four symmetry planes
- Tensions between experimental data of NAC/SPC and state-of-the-art model tunings
→ NAC/SPC provide additional constraints on QGP parameters in Bayesian analyses

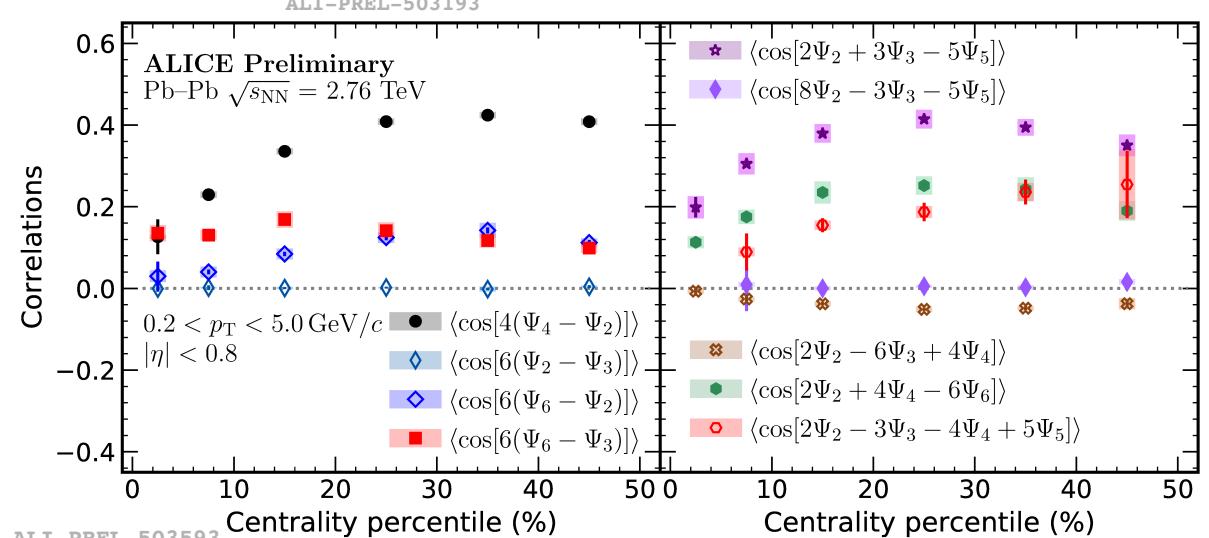
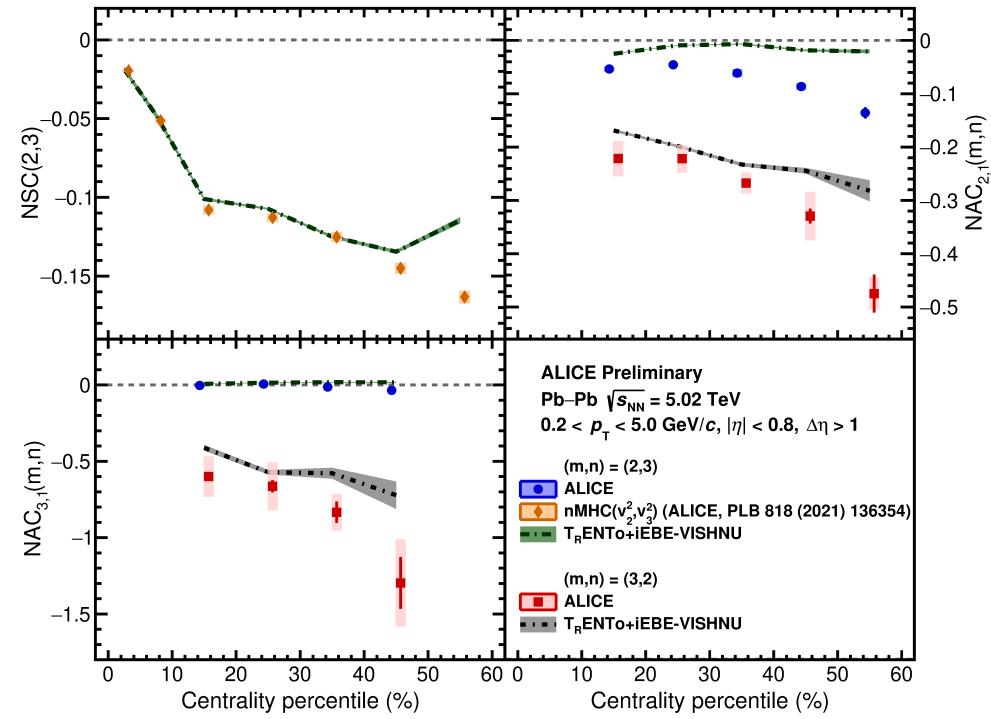




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Thank you!



Additional Slides



Asymmetric Cumulants of v_m and v_n

- Measurements of AC in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$ with ALICE
- General expression of $\text{AC}_{a,1}$

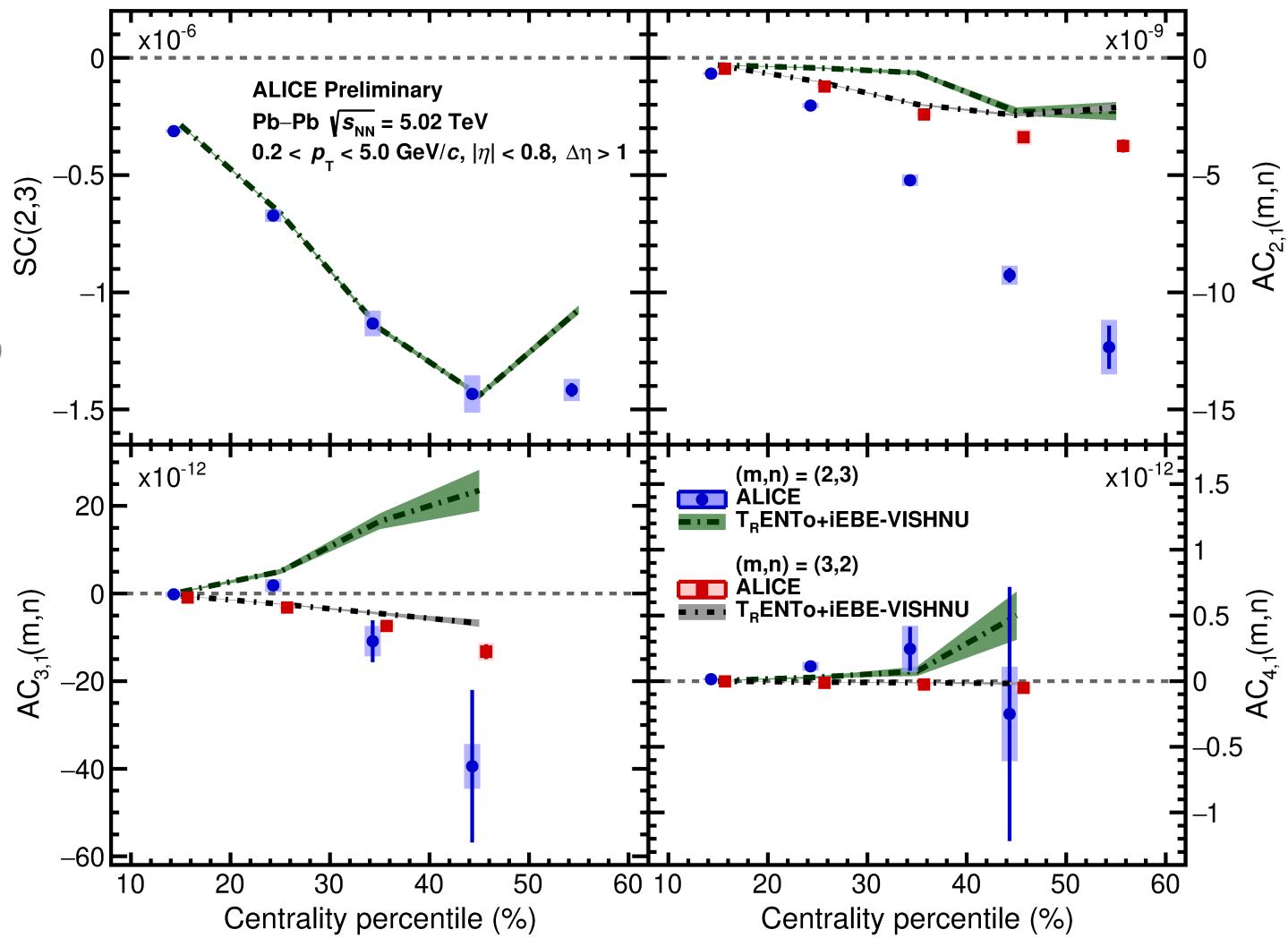
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A. Bilandzic, M.L. C. Mordasini, S.F. Taghavi, PRC 105, 024912 (2022)

- Good agreement between the data and the model for $\text{AC}_{a,1}(3,2)$, not for $\text{AC}_{a,1}(2,3)$
- Decreasing magnitude of $\text{AC}_{a,1}$ for increasing value of index a
- However: increasing value of a increases amount of flow amplitudes



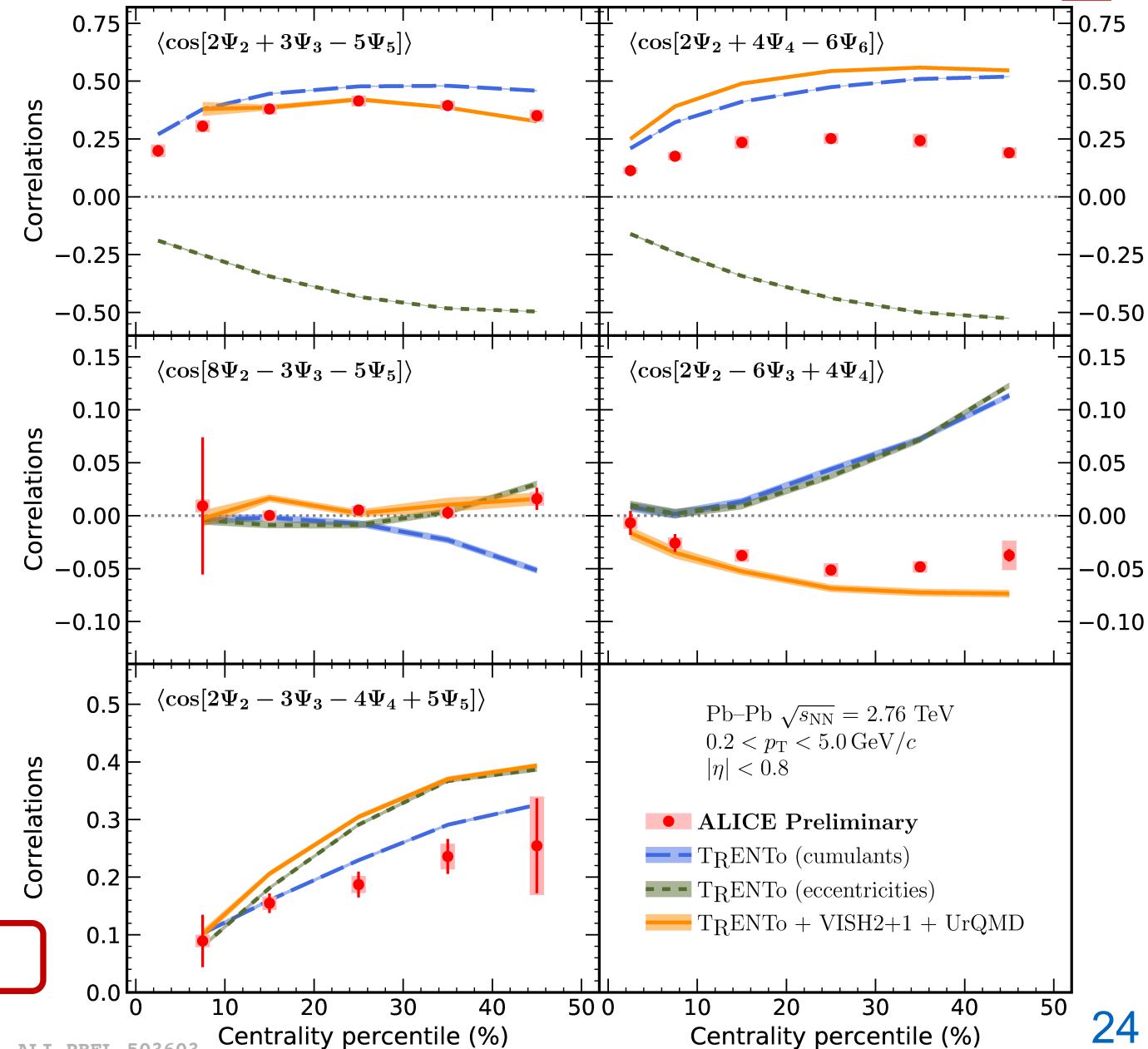
ALI-PREL-503188



Correlations between three and four symmetry planes

- Two combinations for Ψ_2, Ψ_3 and Ψ_5 with different final-state signals
 - Reason: contribution of different initial-state correlations
- Large deviation of the model from measurements in case of Ψ_2, Ψ_4 and Ψ_6
- Negative final-state correlation for Ψ_2, Ψ_3, Ψ_4
 - Sign change during hydrodynamic evolution from initial to final state
- First experimental measurement of correlation between four symmetry planes $\Psi_2, \Psi_3, \Psi_4, \Psi_5$

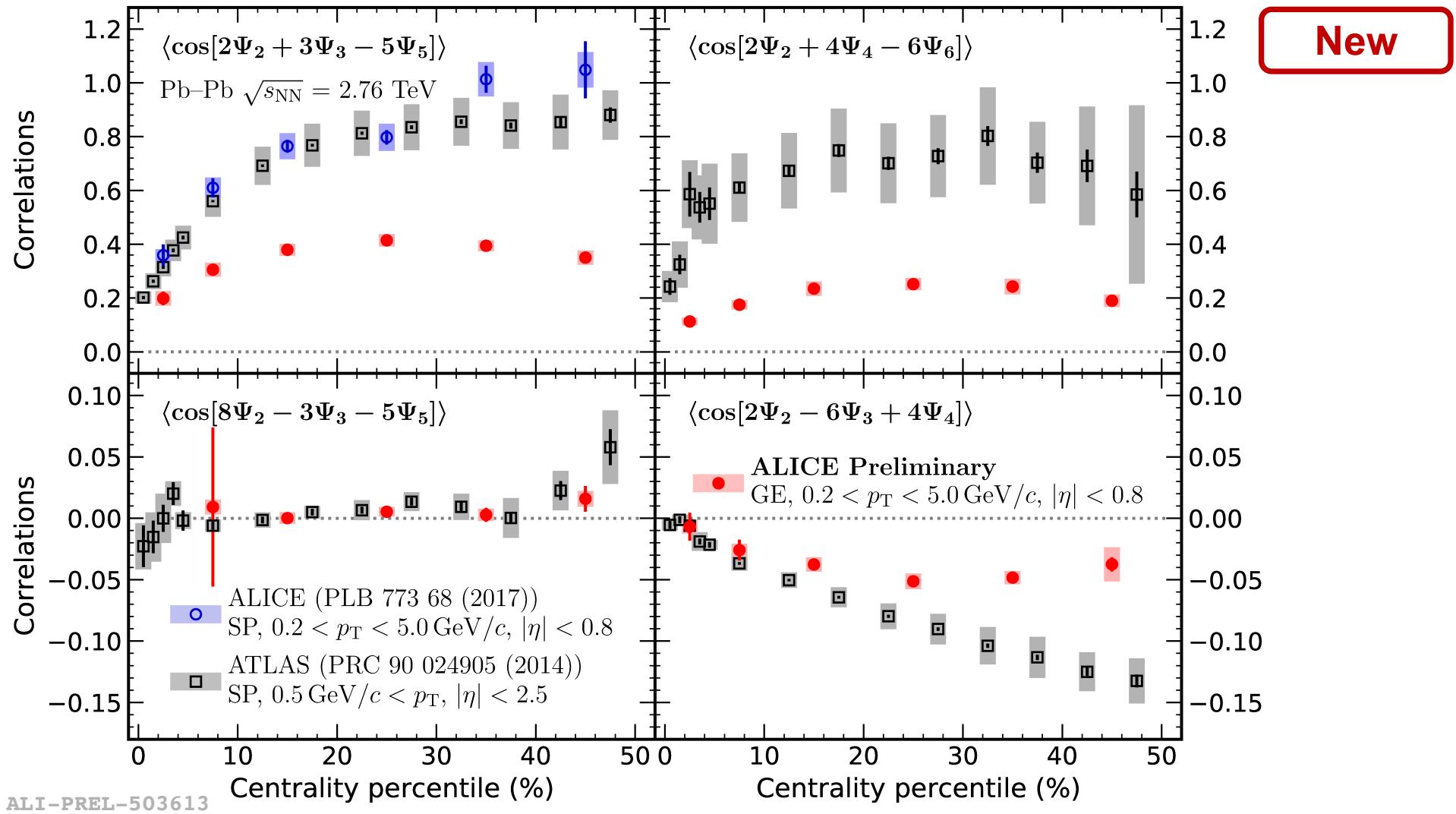
New





Comparison of experimental results from GE and SP

- Results of SPC via GE lead to significantly smaller values than SP method





Gaussian Estimator for SPC

- **Starting point:** Modelling of multi-harmonic flow fluctuations

$\mathcal{R}_x = v_{n_1}^{a_1} \cdots v_{n_k}^{a_k} \cos(a_1 n_1 \Psi_{n_1} + \cdots + a_k n_k \Psi_{n_k})$ and $\mathcal{R}_y = v_{n_1}^{a_1} \cdots v_{n_k}^{a_k} \sin(a_1 n_1 \Psi_{n_1} + \cdots + a_k n_k \Psi_{n_k})$
with a 2D Gaussian

- Use this 2D Gaussian to calculate $\langle \cos(a_1 n_1 \Psi_{n_1} + \cdots + a_k n_k \Psi_{n_k}) \rangle$

→ **Gaussian Estimator (GE):**

$$\langle \cos(a_1 n_1 \Psi_{n_1} + \cdots + a_k n_k \Psi_{n_k}) \rangle_{\text{GE}} = \sqrt{\frac{\pi}{4}} \cdot \frac{\langle v_{n_1}^{a_1} \cdots v_{n_k}^{a_k} \cos(a_1 n_1 \Psi_{n_1} + \cdots + a_k n_k \Psi_{n_k}) \rangle}{\sqrt{\langle v_{n_1}^{2a_1} \cdots v_{n_k}^{2a_k} \rangle}}$$

- Details see:

A. Bilandzic, ML and S. F. Taghavi: “*New estimator for symmetry plane correlations in anisotropic flow analyses*”, PRC **102**, 024910 – 2020